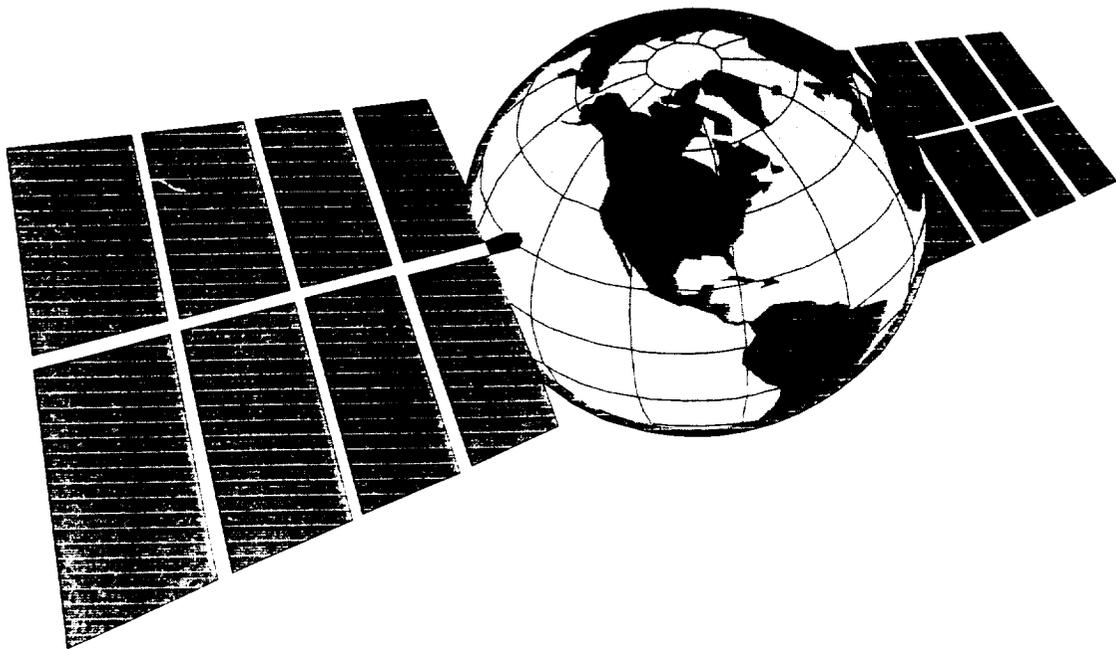
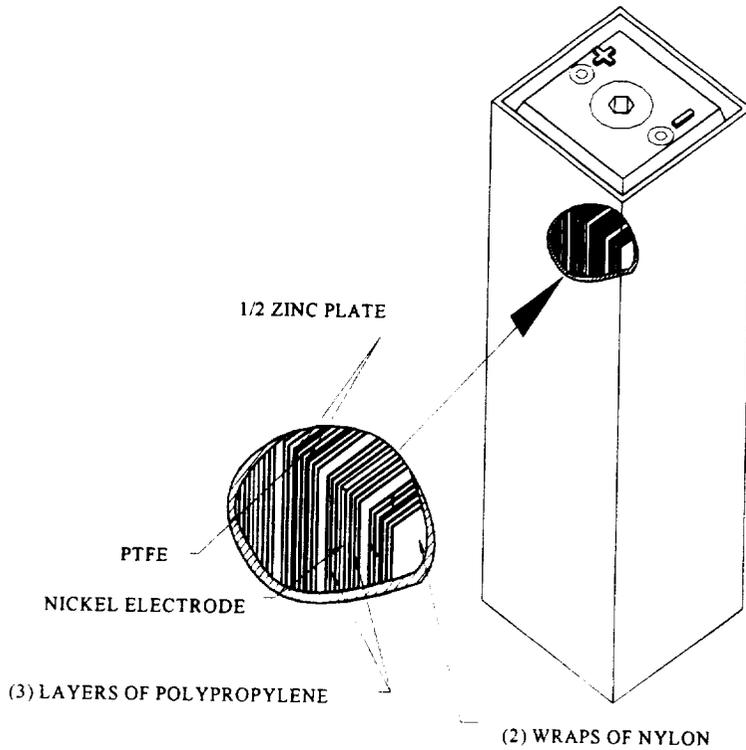


1996 NASA Aerospace Battery Workshop
Marshall Space Flight Center

**LOW-EARTH-ORBIT(LEO) LIFE CYCLE
EVALUATION OF NICKEL-ZINC BATTERIES**

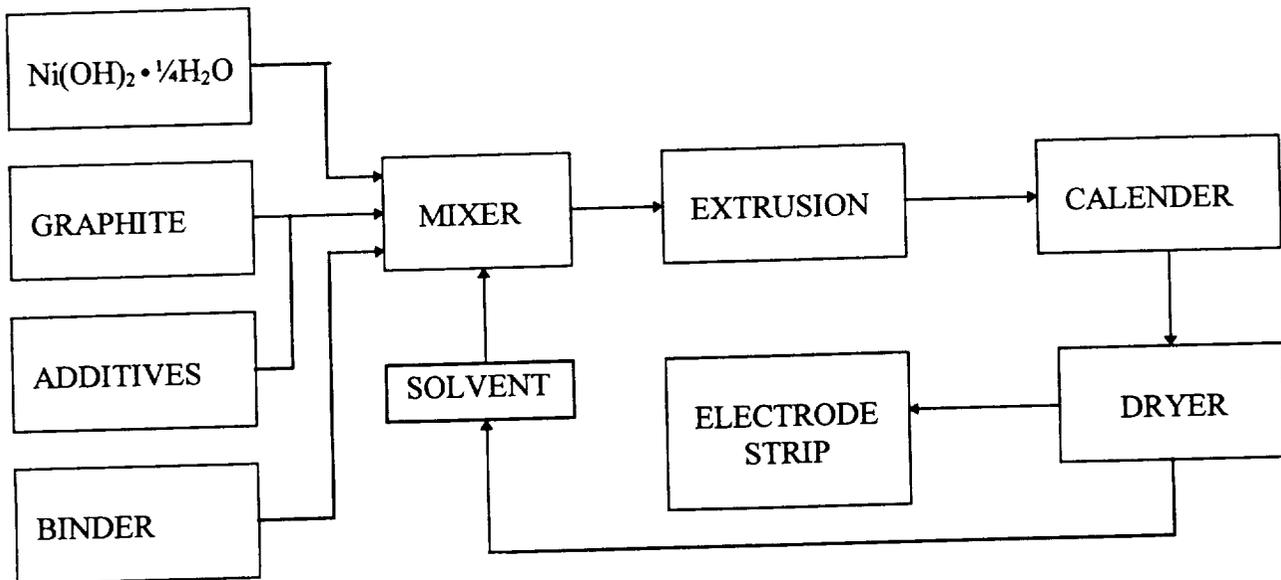


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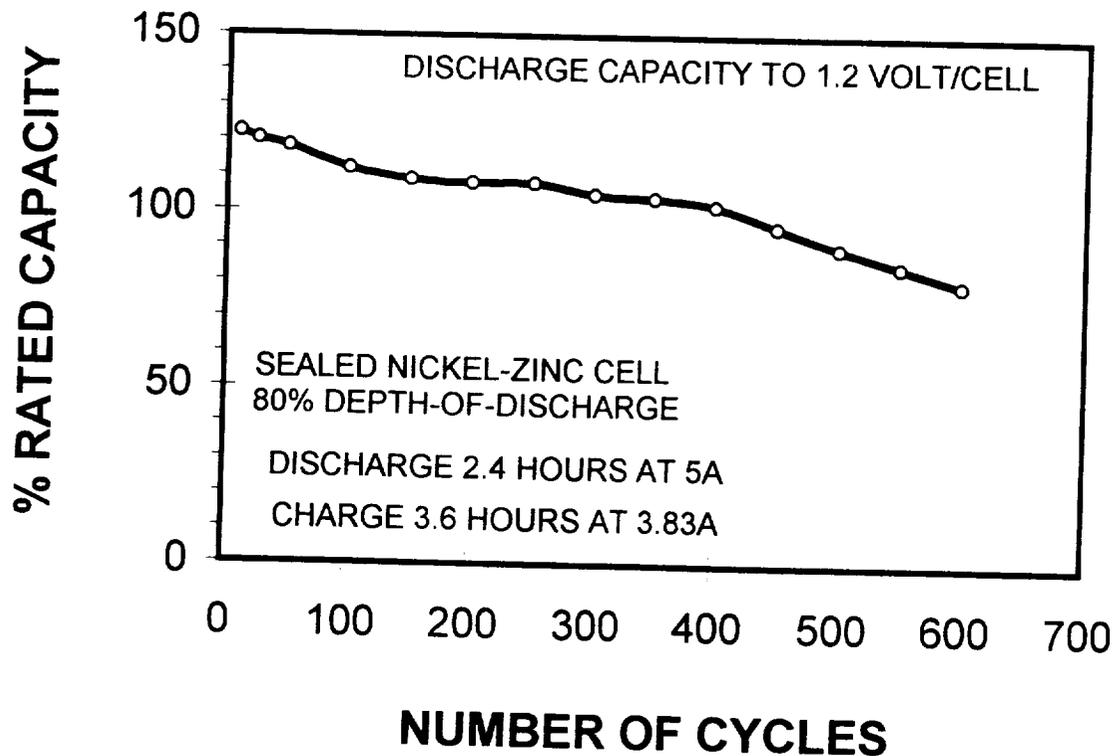
TYPICAL SEALED NICKEL-ZINC CELL DESIGN

- LOW-COST ROLL-BONDED ELECTRODES
- NICKEL/GRAPHITE COMPOSITE ACTIVE MATERIAL
- COBALT SPINEL TREATED GRAPHITE
- LOW METAL CONTENT - HIGH SPECIFIC ENERGY
- REDUCED SOLUBILITY CALCIUM / ZINC ELECTRODE
- MINIMAL SHAPE CHANGE
- POROUS POLYPROPYLENE ZINC MIGRATION BARRIER
- NON-WOVEN NYLON ABSORBER / SEPARATOR
- LOW ELECTROLYTE CONCENTRATION
- 20% POTASSIUM-HYDROXIDE / 1% LITHIUM-HYDROXIDE
- PRISMATIC MOLDED POLYSULFONE CELL CASE
- SOLVENT-WELD COVER TO CASE JOINT
- RESEALABLE PRESSURE RELIEF VALVE (25 psi)



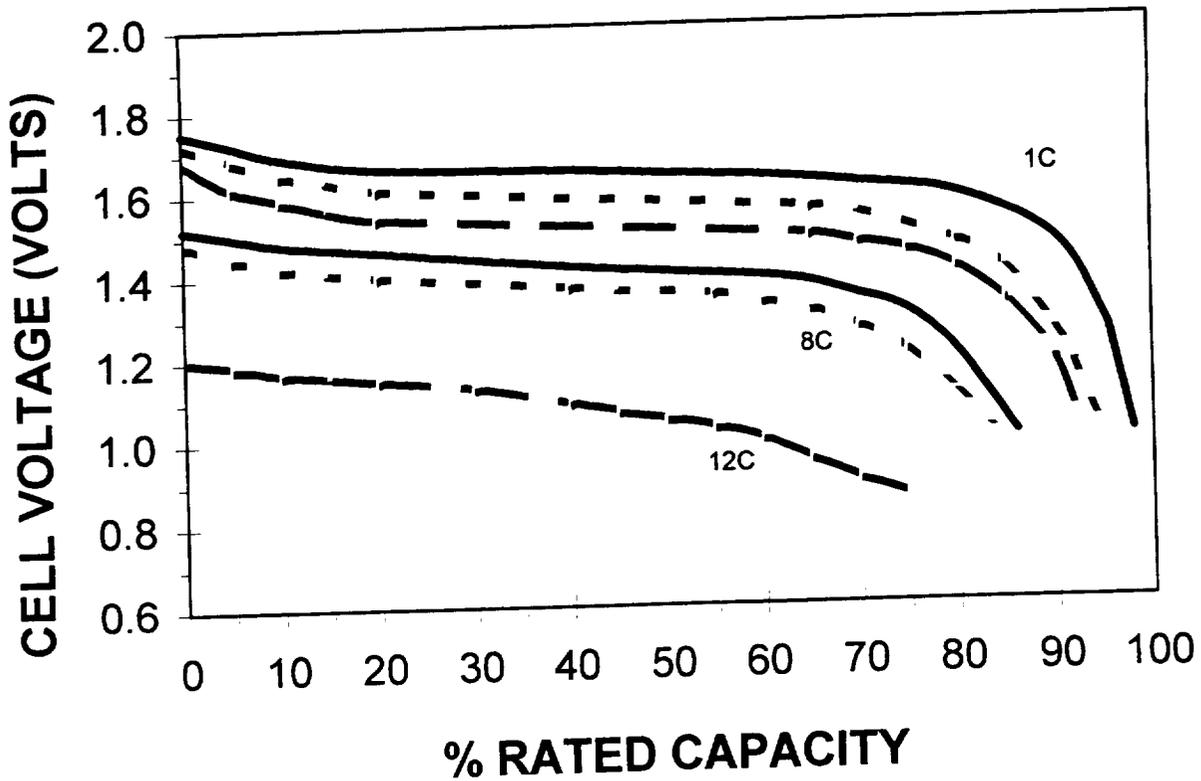
ROLL-BONDED ELECTRODE MANUFACTURING PROCESS

- PATENTED MANUFACTURING PROCESS FOR NICKEL AND ZINC ELECTRODES
- THE NICKEL ELECTRODE IS A GRAPHITE COMPOSITE STRUCTURE
- THE ONLY METAL IN THE NICKEL ELECTRODE IS THE 0.003 INCH NICKEL FOIL CURRENT COLLECTOR
- REDUCED METAL CONTENT REDUCES BOTH COST AND WEIGHT
- THE ZINC ELECTRODE IS A CALCIUM / ZINC FORMULATION
- REDUCED SOLUBILITY ZINC ELECTRODE MINIMIZES SHAPE CHANGE
- LOW COST EXTRUSION BASED MANUFACTURING PROCESS
- PROCESS EASILY SCALEABLE FOR HIGH VOLUME PRODUCTION
- ENVIRONMENTALLY FRIENDLY MANUFACTURING PROCESS
- MINERAL OIL BASED SOLVENT CAN BE RECLAIMED AND RE-USED
- VERY LOW MATERIAL ATTRITION RATE
- ELECTRODE SCRAP MATERIAL CAN BE RE-PROCESSED



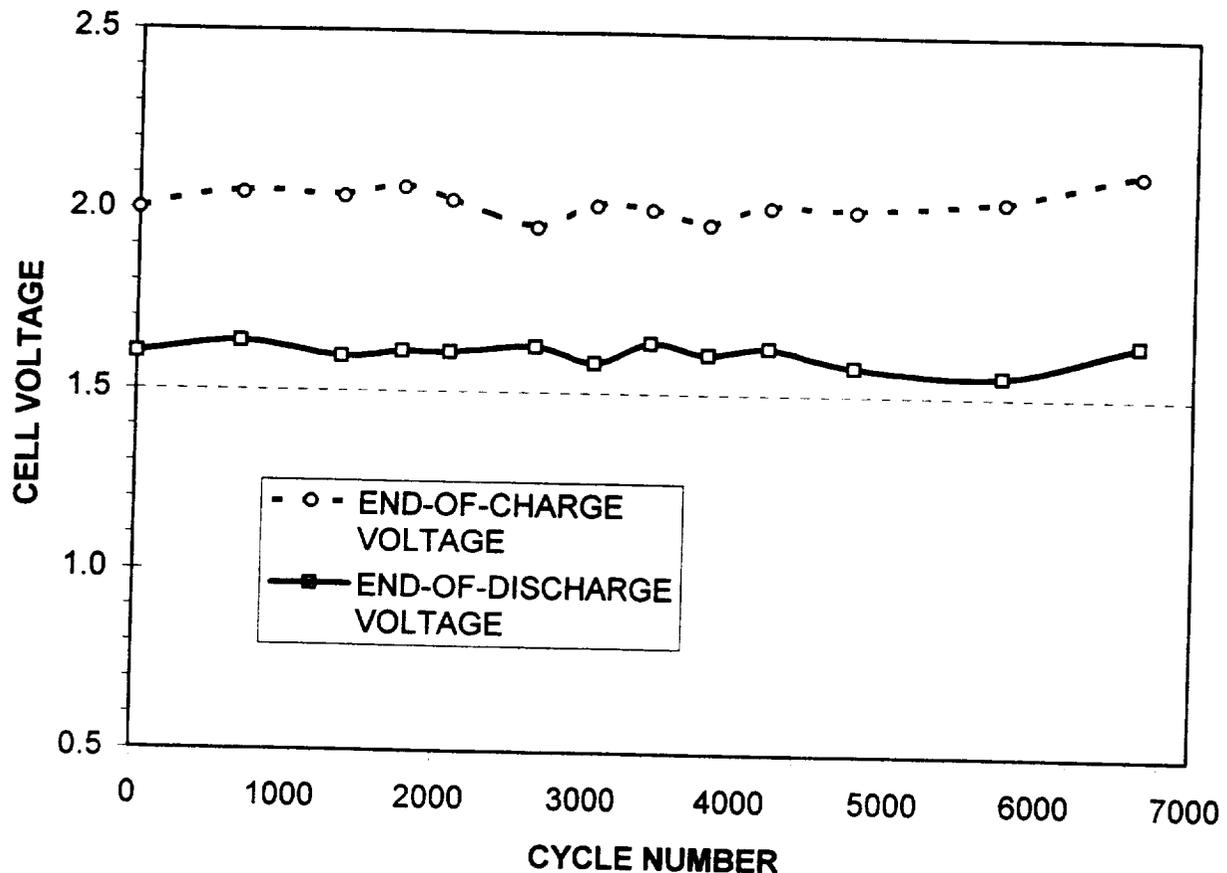
NICKEL-ZINC DISCHARGE CAPACITY VERSUS CYCLE LIFE

- SEALED 15 Ah CELL DESIGN
- ROLL-BONDED COMPOSITE NICKEL AND ZINC ELECTRODES
- PATENTED CALCIUM / ZINC ELECTRODE FORMULATION
- CYCLE REGIME: DISCHARGE @ 5.0 A CHARGE @ 3.8 A
- CAPACITY MEASUREMENT @ 5.0 A TO 1.2 Volts PER CELL
- FULL-DEPTH CAPACITY MEASUREMENT AT 25 CYCLE INTERVALS
- PRIMARY CAPACITY DEGRADATION MECHANISM IS ELECTRODE SWELLING AND CELL STACK DRY-OUT
- ZINC DISSOLUTION AND SHAPE CHANGE ARE MINIMAL



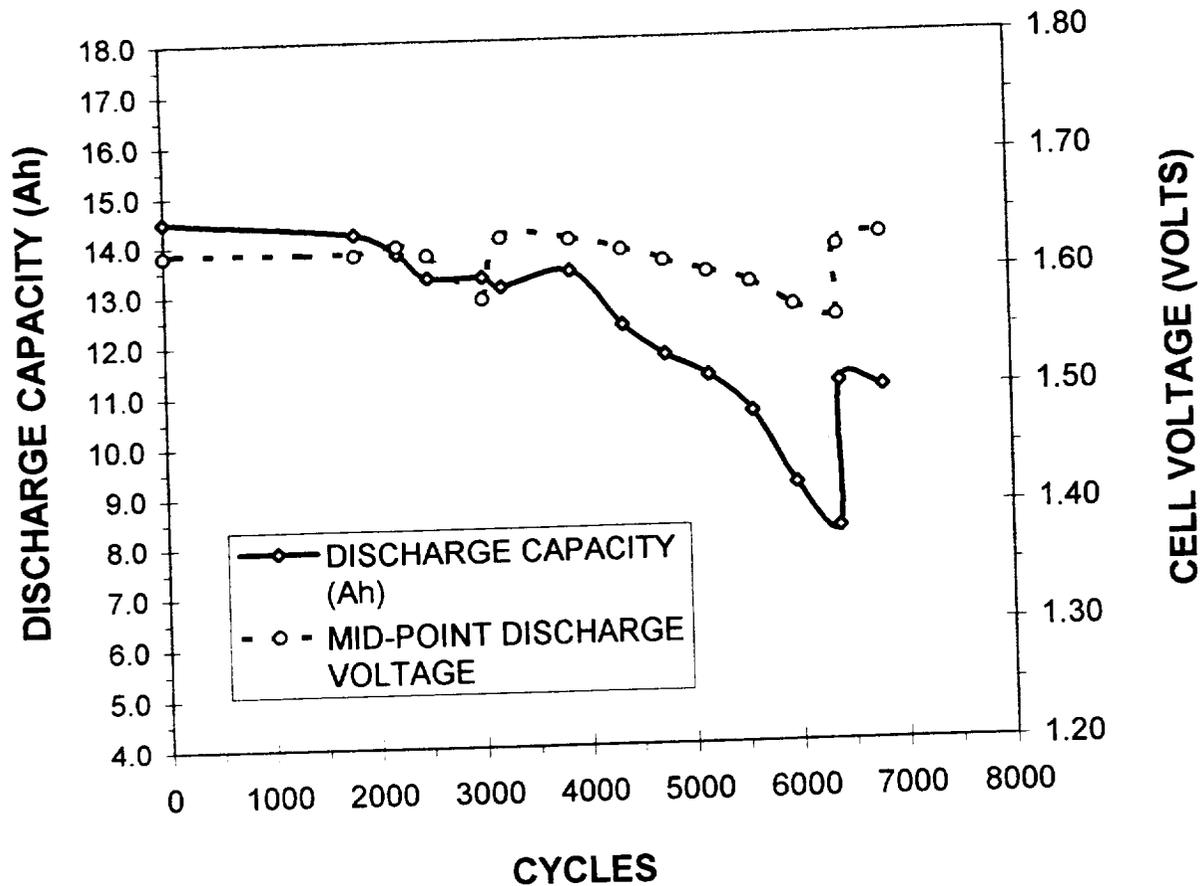
DISCHARGE RATE CAPABILITY OF SEALED NICKEL-ZINC CELL

- SEALED 15 Ah NICKEL-ZINC CELL
- HIGH-RATE DESIGN
- MOLDED POLYSULFONE CELL CASE AND COVER
- PLASTIC BONDED COMPOSITE NICKEL AND ZINC ELECTRODES
- CELL DC INTERNAL IMPEDANCE = 2.5 milliOhms
- DISCHARGE AT 1C, 2C, 4C, 6C, 8C AND 12C (C = 15.0 Amperes)
- ALL DISCHARGES AT ROOM AMBIENT TEMPERATURE
- NO ACTIVE COOLING



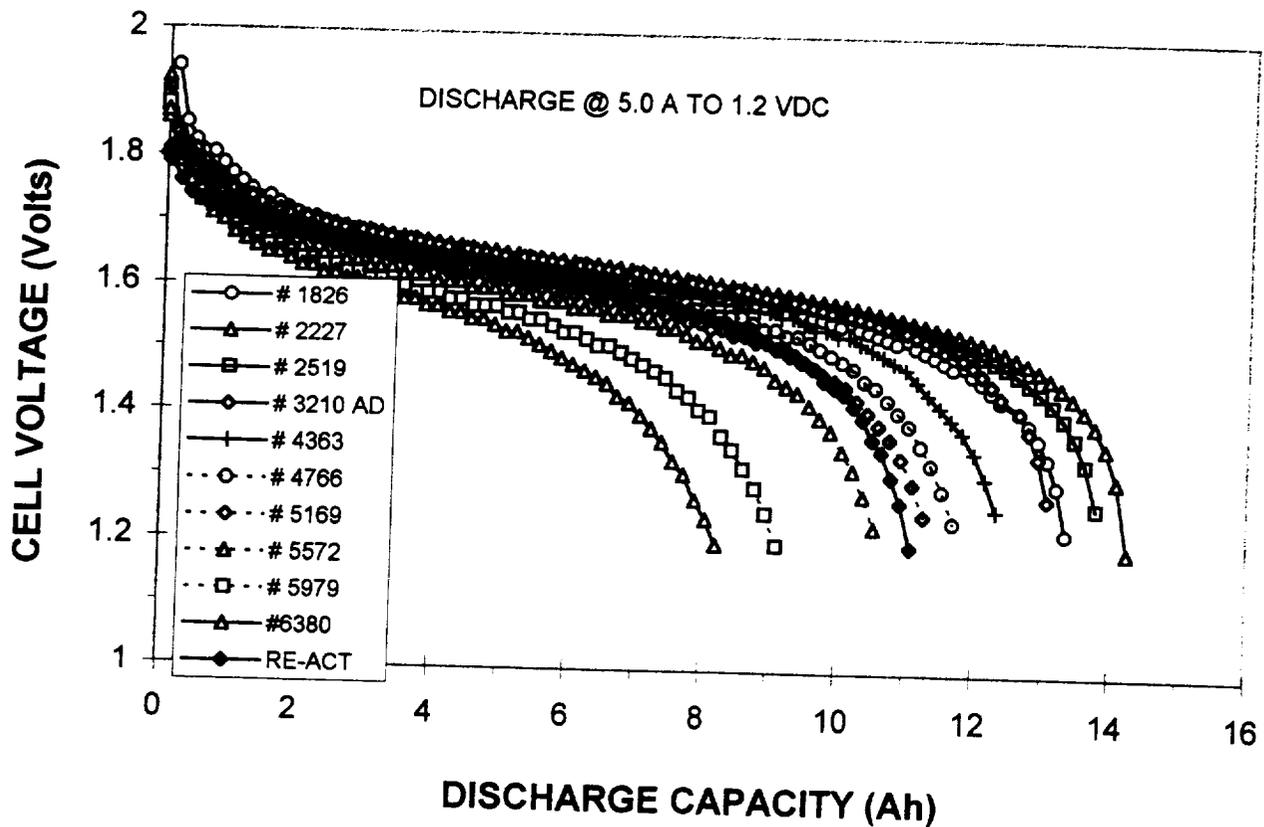
CELL VOLTAGE PERFORMANCE VERSUS CYCLE LIFE

- 14 Ah SEALED NICKEL-ZINC CELL DESIGN
- ROLL-BONDED COMPOSITE NICKEL AND ZINC ELECTRODES
- MOLDED POLYSULFONE CELL CASE AND COVER
- CELL DC INTERNAL IMPEDANCE = 3.0 milliOhms
- CYCLE REGIME: 27.5 MINUTE CHARGE / 17.5 MINUTE DISCHARGE
- CHARGE @ 3.38 A (0.25C RATE) / DISCHARGE @ 5.0 A (0.33C RATE)
- RECHARGE RATIO 1.02 - 1.04
- 10% DEPTH-OF-DISCHARGE BASED ON INITIAL CAPACITY
- CELL OPERATES BETWEEN 80% - 90% SOC BASED ON INITIAL CAPACITY
- CAPACITY MEASURED AT 450 CYCLE INTERVALS
- CELLS REACTIVATED AFTER 6500 CYCLES
- PERFORMANCE IMPROVEMENT AFTER REACTIVATION INDICATES CELL STACK DRY-OUT



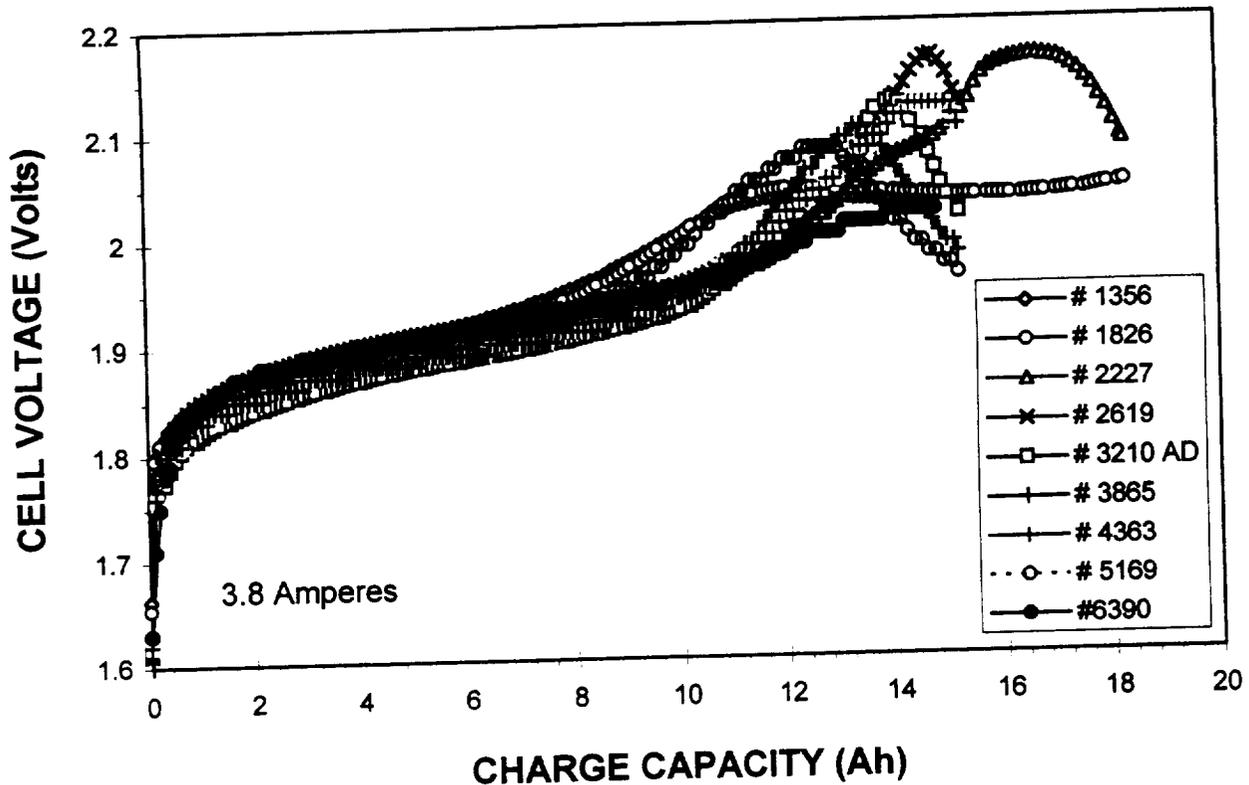
DISCHARGE CAPACITY AND VOLTAGE VERSUS CYCLE LIFE

- TEST ANOMALY OCCURRED AT CYCLE #3130 DUE TO SOFTWARE ERROR
- CELLS WERE BYPASSED ON OPEN-CIRCUIT DURING DISCHARGE PORTION OF CYCLE
- CELLS WERE CHARGED FOR 90 CYCLES WITHOUT DISCHARGE AMOUNTING TO A TOTAL CHARGE INPUT OF 157 Ah (1120% OVERCHARGE)
- CELLS DID NOT VENT DURING THIS EXTENSIVE OVERCHARGE
- PERFORMANCE BEGAN TO DEGRADE RAPIDLY AFTER THIS EVENT
- CELLS WERE REACTIVATED AT CYCLE #6390
- CAPACITY AND VOLTAGE PERFORMANCE IMMEDIATELY RECOVERED
- CELLS CURRENTLY HAVE 75-80% OF ORIGINAL CAPACITY AFTER 7000 CHARGE / DISCHARGE CYCLES



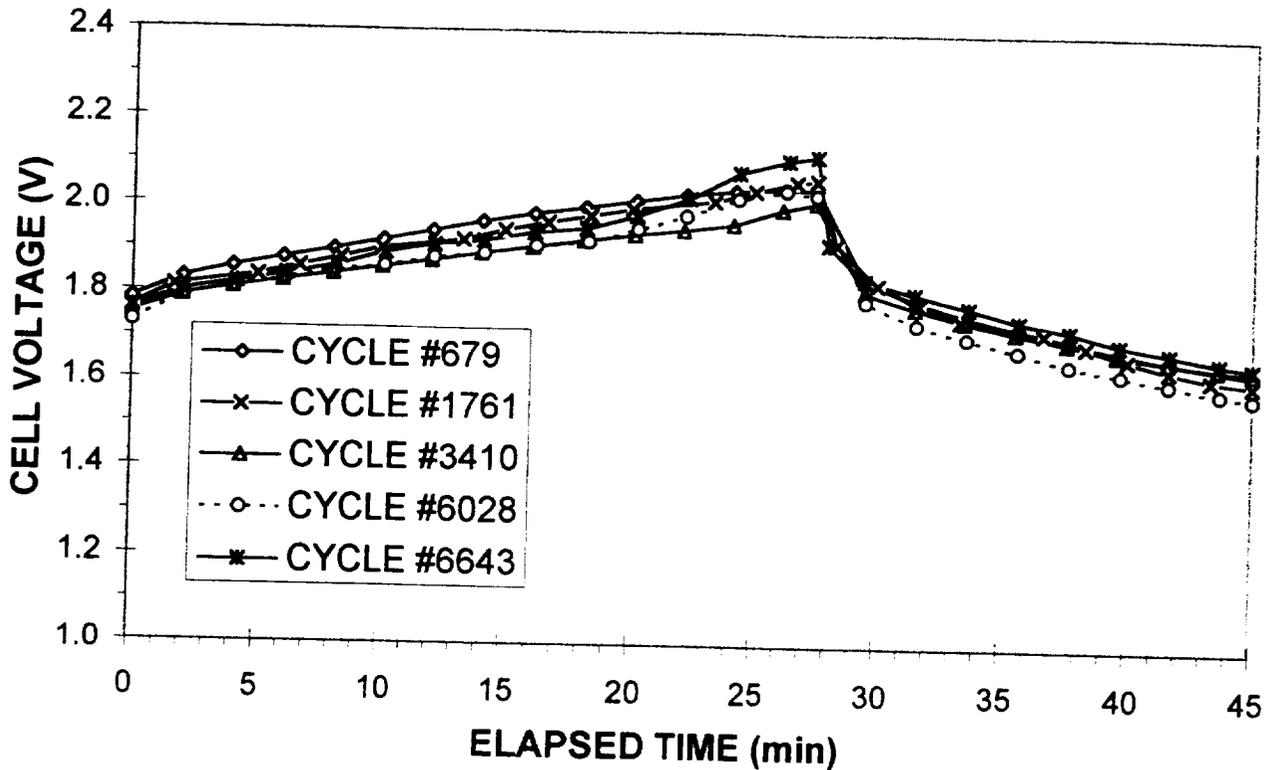
DISCHARGE CAPACITY AS A FUNCTION OF CYCLING

- EACH DISCHARGE IS AT 5.0A TO 1.2V
- PREVIOUS CHARGE FOR EACH CYCLE IS AT 3.8A
- INITIAL CYCLES CHARGE INPUT = 18.0 Ah (28% OVERCHARGE)
- CHARGE INPUT REDUCED TO 15.0 Ah AFTER 2300 CYCLES (8% OVERCHARGE)
- MPDV AT CYCLE #2227 = 1.626V / DECREASED TO 1.560V AT #6380
- INCREASED TO 1.632V AFTER REACTIVATION
- DISCHARGE CAPACITY AT CYCLE #2227 = 13.8 Ah
- DISCHARGE CAPACITY AT CYCLE #6380 = 8.2 Ah (60% OF NOMINAL)
- DISCHARGE CAPACITY INCREASED TO 11.1 Ah (80% OF NOMINAL) AFTER REACTIVATION



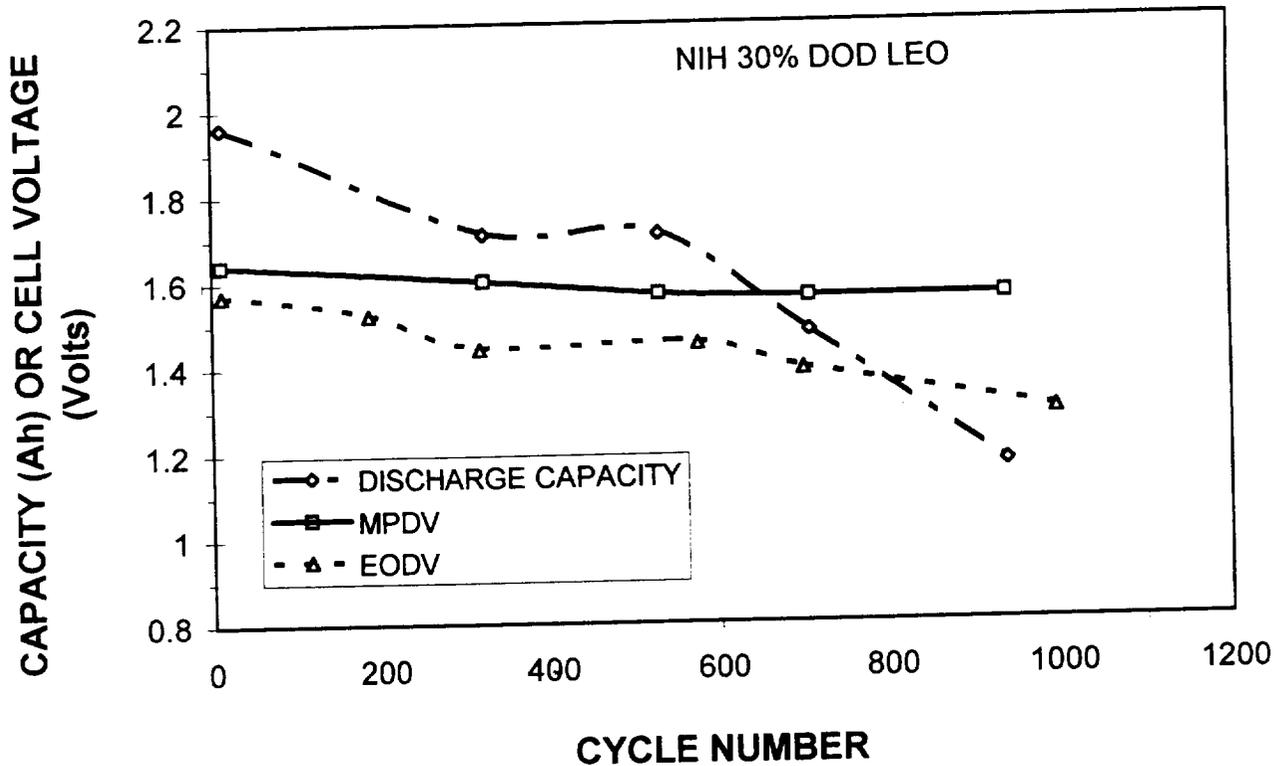
CHARGE VOLTAGE AS A FUNCTION OF CYCLE LIFE

- 3.8A CHARGE PRIOR TO THE FULL-DEPTH CAPACITY MEASUREMENT
- CONSTANT CURRENT / FIXED TIME / AMBIENT TEMPERATURE CHARGE
- OVERCHARGE WAS EXCESSIVE ON INITIAL CYCLES
- TIME WAS REDUCED TO REDUCE TOTAL CHARGE INPUT
- SHAPE OF THE CHARGE CURVE SHOWS A GENERAL TREND TOWARDS THE EARLIER ONSET OF OXYGEN EVOLUTION WITH CYCLING
- THE INFLECTION POINT OCCURS AT 12 Ah FOR CYCLE #2227 (86% SOC BASED ON CELL DISCHARGE CAPACITY)
- THE INFLECTION POINT OCCURS AT 9.5 Ah FOR CYCLE #5169 (116% SOC BASED ON ACTUAL CELL CAPACITY)
- FOR CYCLE #6390 (AFTER REACTIVATION) THE INFLECTION POINT IS AT 12.0 Ah (SAME Ah INPUT AS INITIAL, BUT NOW 109% OF CELL CAPACITY)
- ALSO, CYCLE #6390 SHOWS VERY LITTLE RISE IN VOLTAGE WITH THE ONSET OF OXYGEN EVOLUTION



CELL VOLTAGE VERSUS TIME FOR MULTIPLE LEO CYCLES

- CYCLE REGIME: 27.5 MINUTE CHARGE / 17.5 MINUTE DISCHARGE
- CHARGE @ 3.38 A (0.25C RATE) / DISCHARGE @ 5.0 A (0.33C RATE)
- INITIAL RECHARGE RATIO = 1.04 / CURRENT RATIO = 1.02
- 10% DEPTH-OF-DISCHARGE BASED ON INITIAL CAPACITY
- DOD = 15% BASED ON CURRENT CAPACITY AFTER 7000 CYCLES
- CELL OPERATES BETWEEN 80% - 90% SOC BASED ON INITIAL CAPACITY
- CURRENTLY OPERATING BETWEEN 75% - 90% SOC
- MPDV AT #679 = 1.711V / DECREASED TO 1.660V AT CYCLE #6028
- MPDV INCREASED TO 1.724V AFTER REACTIVATION
- EODV AT #679 = 1.633V / DECREASED TO 1.580V AT CYCLE #6028
- EODV INCREASED TO 1.652V AFTER REACTIVATION



DISCHARGE CAPACITY AND VOLTAGE VERSUS CYCLE NUMBER

- 2 Ah SEALED NICKEL-ZINC CELL
- SPECIFIC ENERGY = 60 Watt-hours per kilogram
- ENERGY DENSITY = 73 Watt-hours per liter
- CELL DC INTERNAL IMPEDANCE = 30 milliOhms
- CYCLE REGIME = 27.5 minute CHARGE @ 1.3 A
17.5 minute DISCHARGE @ 2.0 A
- 30% DEPTH-OF-DISCHARGE BASED ON INITIAL CAPACITY
- DISCHARGE CAPACITY MEASURED @ 1.0 A TO 1.2 Volts PER CELL
- MPDV = MID-POINT DISCHARGE VOLTAGE DURING ACC LEO CYCLE
- EODV = END-OF-DISCHARGE VOLTAGE AT TIME = 45 minutes DURING THE NORMAL ACCELERATED LEO CYCLE

CONCLUSIONS

- COMPOSITE NICKEL ELECTRODE PROVIDES EXCELLENT PERFORMANCE AT A REDUCED WEIGHT AND LOWER COST
- CALCIUM / ZINC ELECTRODE MINIMIZES SHAPE CHANGE
- UNOPTIMIZED CELL DESIGNS YIELD 60 Wh/kg
- NICKEL-ZINC DELIVERS 600 CYCLES AT 80% DOD
- LONG CYCLE LIFE OBTAINABLE AT LOW DOD
 - > 7000 CYCLES AT 10% DOD
 - > 1000 CYCLES AT 30% DOD
- HIGH RATE CAPABILITY / POWER DENSITY
- LONG-TERM FAILURE MECHANISM IS STACK DRY- OUT
- METAL CASE CELL DESIGN UNDER DEVELOPMENT
- FURTHER TESTING PLANNED AT 50% DOD
- FURTHER WORK PLANNED TO REDUCE ZINC TO NICKEL RATIO
- ANOMALOUS OVERCHARGE (1120%) GREATLY AFFECTED CELL PERFORMANCE BUT DID NOT INDUCE FAILURE AND WAS RECOVERABLE